Generation of High Resolution Topographic Maps of the Galapagos Islands Using TOPSAR Data

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ABSTRACT

Data collected over the Galapagos Islands using the JPL/NASA TOPSAR airborne interferometric radar covered an area in excess of 5000 km². 'I'his paper presents the algorithms used to mosaic the data into a high resolution (1 Ox 10 m ground spacing) topographic map of the islands. Also described are the correlation and height error maps which are generated as ancillary products to the topographic map.

INTRODUCTION

In the summer of 1993 the JPL/NASA TOPSAR airborne interferometric radar collected data covering the islands of Isla Isabela and Isla Fernandina in the Galapagos chain as shown in Figure 1. These islands have a combined surface area of 5230 km^2 and have elevations ranging from sea level to over 1700 m. A total of fifteen TOPSAR passes were collected with 12 km wide swaths in the cross track direction and in strips ranging from 30 to 100 km in length in the along track direction, Cross track mosaicking of the data by dead reckoning is not possible because the aircraft and TOPSAR navigation systems are not sufficiently accurate to produce DEM's of the required accuracy using this approach. To align the data vertically tiepoints taken along the coastline were used to remove an cross track slope, along track slope, and height offset. A quadratic warping of the heights between adjacent image strips was also required to remove long term drifts in the navigation data. An affine transformation was least-square fitted to tiepoints in the overlap region of each of the strips , The transformation included an arbitrary three dimensional rotation, scaling in the along and cross directions, skew, and a translation. Data for onc strip was then cornbincd with data from an adjacent strip using this transformation. To avoid amplitude and height discontinuities in the final DEM a feathering algorithm was employed for data in the overlap region between the strips.

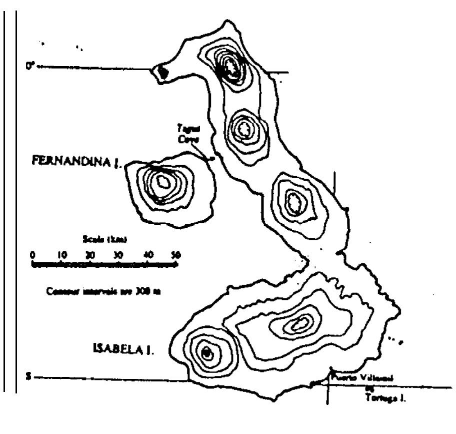

Figure 1. Map of Isla Isabela and Fernandina.

TOPSAR INSTRUMENT

The TOPSAR (Topographic Synthetic Aperture Radar) system has been described in detail elsewhere [Zebker, 1992] and therefore only the relevant details will be summarized here. TOPSAR system parameters in the configuration flown in the Galapagos are given in Table I.

The TOPSAR system uses two antennas which are flush mounted to the left side of the DC-8. The antennas are mounted at the same along track position and with a separation of 2.6 m in the cross track plane. One antenna is used for transmission and radar echoes received by each of the two antennas are recorded independently. The slant range resolution which is inversely proportional to the range bandwidth is 3.33 m and the slant range swath is 8450 m after range compression,

The aircraft is equipped with three navigation systems. The digital avionics data system (DADS) includes the aircraft's inertial navigation system, a barometric altimeter, and a radar altimeter. The second system is a global positioning system (GPS) operated using civilian access codes, and the third system is the radar's inertial navigation system (LASERREF). Both the DADS and GPS system are reasonably accurate (75-1 00 m for the GPS) but the update rate is only once per second (which is slow compared to the radar pulse rate of 800 Hz). The LASERREF provides accelerations and aircraft attitude at a 50 Hz rate, however, since it is not linked to the other systems biases in position, elevation, and velocities tend to increase over time. In order to use the higher frequency update data from the LASERREF it is necessary to combine it with either the low frequency GPS or DADS data to remove the long term drifts as described in [Madsen, 1992]. Selection of whether to use DADS or GPS data as the low frequency reference depends on the availability and quality of the GPS data.

Table I. TOPSAR Parameters

Radar Parameter	Value
Frequency	5.3 Ghz
Range Bandwidth	40 Mhz
Peak Transmit Power	1000 W
Pulse Repetition Rate	3.9 pulses/m
Antenna Length	1.5 m
Antenna Elevation Beamwidth	30°
Baseline Length	2.6 m
Baseline Angle wrt Horizontal	62.8°
perating Altitude	8450 m
Look Angles	23°-63°
Slant Range near/far	9913 - 18361 m
Processed Ground Swath	12 km

DATA COLLECTION

The Galapagos Archipelago consists of thirteen islands with a surface area greater than 10 km^2 plus a number of smaller islands and islets, They are located 960 km west of Ecuador with most of the islands lying between the equator and 10 South latitude and between 90° and 92° West longitude. The largest island in the archipelago is Isla Isabela with a land area of 4588 km^2. Isla Fernandina, the third largest island the in archipelago lies to the west of Isla Isabela and has land area of 986 km^2. See Figure 1 for a map. Interest in mapping these islands stems from the fact they are among the most active oceanic volcanic regions on earth. Isla Isabela has had eruptions as recently as 1979 and much of Fernandina's 7 km^2 caldera floor collapsed by as much as 300 m in 1968.

Three sets of parallel flight lines were used to collect TOPSAR data. Adjacent fight lines were arranged so as to try and maintain 2-4 km of overlap. The northern part Isabela was mapped with four parallel mapping passes of 100 km in length. The western part of the island was imaged from the west with an aircraft heading of 1 SO° and the eastern part of the island was imaged from the east with a heading of 330°. Data over the southern part of the island was collected using six mapping of 100 km in length. The top part of the southern portion of the island was imaged from the north with an aircraft heading of 70° and the bottom was imaged from the south with an aircraft heading of 250°, Fernandina was imaged with 40 km long mapping passes along strips with aircraft headings alternating between 150° and 330°. Figure 2 shows the mapping passes over Isabela and Fernandina.

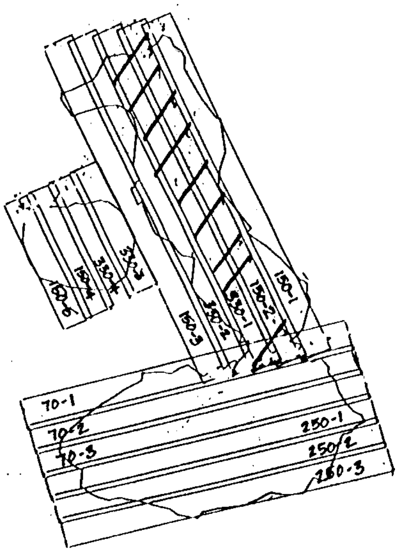

Figure 2. Mapping swaths on Isla Isabela and Fernandina

PROCESSING

All fifteen of TOPSAR mapping passes were processed using a slightly modified version of the integrated TOPSAR processor described previously [Madsen,1993]. The first modification was included a correlation map coregistered with the DEM as an output product. Using the correlation map a height error map associated with random errors can bc generated using expressions equivalent to those found in [Rodriguez, 1992]. From [Rodriguez,1 992] the contribution to height uncertainty from phase noise σ_ϕ (here phase noise refers to interferometric phase noise between the two radar channels) is given by

$$\sigma_h = \frac{\lambda\rho}{2\pi B}\frac{\sin(\theta)}{\cos(\alpha-\theta)}\sigma_\phi \qquad (1)$$

where λ is the radar wavelength, ρ is the range from the aircraft to target, θ is the look angle, B is the baseline length, and α is the baseline angle. The Cramer Rao bound to estimate the phase variance from the decorrelation coefficient γ, [Rodriquez, 1992] is

$$\sigma_\phi = \frac{1}{\sqrt{2N_L}}\frac{\sqrt{1-\gamma^2}}{\gamma} \qquad (2)$$

where N_L is the number of looks and γ is obtained from

$$\gamma = \frac{|\beta|}{1+SNR^{-1}} \qquad (3)$$

In equation 3 the quantity 1- $|\beta|$ is the geometric decorrelation given by

$$1-|\beta| = \frac{\rho_r B_\perp}{\lambda\rho\tan\theta} \qquad (4)$$

and ρ_r is the slant range resolution and $B_\perp = B\cos(\alpha-\theta)$ is the perpendicular baseline.

Subsequent to processing the correlation maps showed a banding in the along track direction which at first was not understood. This was latter traced to the digital handling system on board the aircraft mixing P-band pulse data with the C-band TOPSAR data. The lowered correlation in these areas results in an rms increase in the height errors of about 2 m.

A flight track alignment error between the two passes (the cross hatched tracks in Figure 2) running along central part of the northern region of Isabela resulted in a gap of 2 km in coverage over the three volcanoes on that part of the island. The processor was modified use part i all y range compressed data in the near range to fill in the gaps, This resulted in a reduction in resolution and increase in the height error for points in the gap areas. The rms height error increased by approximately 2 m in these areas.

MOSAICKING

Mosaicking of TOPSAR data is a three dimensional problem and thus requires a different approach when compared with techniques normally used to mosaic two dimensional SAR imagery. Provided the navigation data (position, velocity and aircraft attitude) were sufficiently accurate it would be possible to use dead reckoning techniques to mosaic the TOPSAR mapping passes. This was not the case at the time the Galapagos data was collected which necessitated a somewhat more complex procedure.

Since no fiducial corner reflectors or landmarks were available with the Galapagos data the coastline was used for reference points. Mapping passes having little coastline were referenced to the coast using tiepoints from adjacent strips that had previously been referenced to the coast. Tiepoints along the coast (or to a previously referenced image) were selected and the differences between the TOPSAR heights in the current image and TOPSAR heights in the reference image (an assumed height of zero is used for coastal tiepoints) were least square fitted to a quadratic polynomial of the form

$$\Delta h(x,y) = a_0 + a_1x + a_2y + a_3xy + a_4xy^2 \qquad (5)$$

where Ah denotes the height difference, x is the cross track position, and y is the along track position, The TOPSAR heights were then warped 'by subtracting the fitted height difference from the TOPSAR heights. The quadratic term in the along track direction was needed to compensate for relative height errors in the aircraft altitude from pass to pass. These relative height errors were a result of uncompensated GPS clock drift in the GPS receiver.

To mosaic the adjacent passes containing overlapping areas an affine transformation of the form

$$f(\vec{x}) = \text{Rot Skew Scale}(\vec{x}) + \vec{T} \qquad (6)$$

where Rot is an arbitrary rotation matrix, Skew is a skew matrix in the cross track-along track plane, Scale is a matrix scaling the length along the three axes, and $\vec{T}$ is a translation vector, is least square fitted to tiepoints between the two images. Using the affine transformation computed from the tiepoints the second image and height data are resampled to the coordinate system of the first image. For points in the overlap region between the two data sets a feathering scheme is implemented to smooth amplitude and heights between the two images. The correlation maps are also mosaicked using the two dimensional portion of the affine transformation. Correlation maps were used to generate height error maps using equations 1-4.

The height error maps show an height accuracy of about 1-2 m over most of the image except in areas corrupted by the P-band pulse data and in the areas where only partially compressed pulse data was available. The absolute height accuracy is estimated to be 20-30 m , The larger absolute height accuracy is a result of the height warping needed to compensate for the GPS clock drift errors.

CONCLUSION

This paper discussed an algorithm suitable for mosaicking inteferometrically generated digital elevation and image data collected over large areas, The images were mosaicked using an affine transformation that accounted for rotation, translation, scale along all three axes and skew in the image plane. The rotation was determined from tiepoints in the overlap region of adjacent image strips. Lacking surveyed corner reflectors or other landmarks to act as fiducial points overall tilt and vertical translation errors were removed using tiepoints along the coast. Height error maps produced from the interferometric correlation maps show height errors generally between 1-3 m expect in areas where data was corrupted due to P-band pulses being intermixed with the TOPSAR data and in overlap gap region on Isabela where partially compressed pixel data was used.

ACKNOWLEDGMENT

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